2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #52353

BSCER: Capacity Building for Developing a Troubleshooting Learning Environment

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BCSER: Capacity Building for Developing a Troubleshooting Learning Environment – Results from Year 1

Abstract

Troubleshooting is a pervasive challenge in engineering practice, yet a few validated learning frameworks explicitly target the development of troubleshooting expertise. This NSF-funded Building Capacity for STEM Education Research (BCSER) project aims to design a learning environment that cultivates adaptive troubleshooting skills, framing troubleshooting as a diagnosis-solution problem type.

During Year 1, we investigated the key cognitive competencies underlying successful troubleshooting. We conducted in-depth interviews with 18 engineers, each with over 10 years of industrial (n=14) or academic research experience (n=4), to examine how they perceive and manage complexity. The experts' reflections revealed four primary categories of complexity, including system representation, information ambiguity, situational, and stakeholder types. Our analysis further showed how experts draw on prefigurative schemas to regulate knowledge types and reasoning strategies when addressing complex, ill-structured problems.

We further examined experts' reasoning processes using think-aloud problem-solving protocols focused on specific complexity categories. From these, we developed a conceptual model of troubleshooting expertise and identified the initial elements for designing a learning environment that supports adaptive reasoning and knowledge flexibility in complex problem contexts.

Introduction

Troubleshooting has been defined and described in various ways across disciplines, with a rich body of literature examining its cognitive demands [1-7]. A concise synthesis of this literature is provided below. Troubleshooting begins when a system produces a discernibly substandard output, signaling a deviation from expected performance. The underlying root cause, typically an unknown fault such as a broken, incompatible, misused, or an aging component, is initially uncertain. To identify the root cause, the problem solver conducts a systematic search that starts from the presenting symptoms and progresses through the system's components and their states. This search involves divergent exploration of a possibility space, where hypotheses about likely causes are continuously generated and tested until the root cause is identified. Once the process is complete, the solution phase involves remediation, repairing, replacing, or redesigning the faulty component. These tasks alternated between divergent (exploring possible causes) and convergent (narrowing to a specific diagnosis) cognitive models. Importantly, the process is seldom linear; tasks are revisited as new evidence emerges. This general diagnosis-solution structure is observed consistently across domains, such as technical maintenance, circuit or software debugging, clinical diagnostics, and engineering troubleshooting [8-12].

This iterative diagnosis-solution structure becomes especially challenging when troubleshooting complex engineering problems, where hidden interactions, ambiguous system boundaries, and rich information make the search space vast and ill-structured. While domain knowledge is indispensable as a foundational toolbox, engineering and science education often delivers it in overly simplified and siloed ways through well-structured problems [13-19]. This reductionist approach, although effective for teaching basic concepts and solving well-structured problems, fails to equip students for solving complex real-world problems characterized by entangled and unconstraintэd factors [20-22].

In Year 1 of our grant work, we examined the task structure of experts' troubleshooting episodes and characterized the complexity associated with their narrated experiences. In addition, we investigated how experts operationally use their expertise to solve ill-structured engineering problems. In the subsequent sections, we describe our methods of inquiry and results, followed by a conclusion section.

Methods

Cognitive Task Analysis: Our central hypothesis is that the capacity to troubleshoot is characterized by the ability to flexibly apply and reorganize knowledge across multiple representations, problem contexts, and levels of abstraction, consistent with Cognitive Flexibility Theory [23]. In this view, we investigated how experts integrate emergent information to dynamically restructure component functions shifting between localized failure analysis and system-wide reasoning in a flexible manner. For this purpose, we prepared a case study involving a pneumatic system that integrates control equipment with mechanical systems such as a pressure vessel and a compressor. We left the study intentionally ill-structured by revealing only some cues but keeping the study consistent. With this move, we wanted to gauge experts' response to this lack of structure. We asked participants to verbalize their thoughts solving the problem following a simple think-aloud warm-up exercise and reading a descriptive narrative explaining key domain principles related to the study. We have interviewed six individuals in total; however, in this study, we present results from two individuals, an engineer with at least 10 years of experience and a PhD student at our institution. Both engineers identified as male. The system in the case study is shown in Figure 1.

Semi-structured Interviews: We adopted a qualitative design that used semi-structured interviews because we sought insight into how experienced engineers represent systems during troubleshooting episodes, how they register complexity, and how they sequence actions as situations evolve. Our protocol invited engineers to explain how they constructed and revised system models, how they recognized complexity in practice, how they moved between familiar and unfamiliar situations, and how their epistemic stances supported action under uncertainty. We used purposive sampling to recruit participants with ten or more years of engineering experience. We sought this level of experience because repeated exposure to product cycles and large case histories often supports the formation of robust schemas that help experts revise representations when familiar patterns fail [2, 24]. We aimed for variation in domain so that we could examine reasoning across different technical and organizational settings. Our sample (n=18) included engineers in manufacturing, medical devices, robotics, defense systems, power electronics, software and CAD platforms, and academic research, typical of mechanical engineering related industries. We stratified samples based on gender, highest academic degree, and industry type, which were Biomedical, Robotics, Defense, Manufacturing, Product Design and Thermal sciences. We allowed interviewees to be grouped across industry types. For example, if an engineer worked on medical robotics, the resulting codes are tagged with both Biomedical and Robotics. We recorded all interviews with consent and transcribed them verbatim. Out of 18 interviewees, 17 identified as male and one as female. Ten interviewees had PhD, two MS, and six BS as their terminal degrees. We anonymized transcripts during preparation for analysis and removed details that could reveal proprietary systems or sensitive projects. The study was approved by IRB board of our institution.

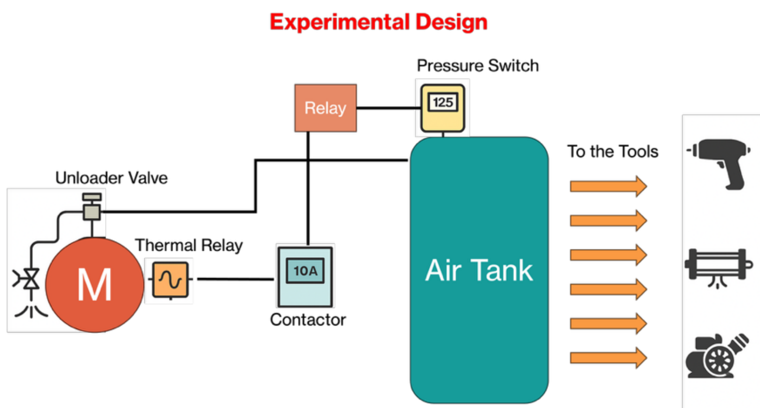

Figure 1. A schematic for the case study given to subjects. In the study the presenting symptom is that the compressor has begun shutting down intermittently, usually after ~2 minutes of run time. Operators report increased start-up cycles. The motor housing is unusually hot to the touch. The tank pressure (as measured by the manual pressure gage on the air tank) at the moment of compressor shutdown is consistently 20 to 25 psi less than the cut-out threshold.

Preliminary Results

Cognitive Task Analysis. We coded the transcripts using a mix of deductive and inductive schemes. We separated operational troubleshooting, which includes system modeling and root cause analysis, from epistemic stance and self-awareness. The resulting themes included "Epistemic Stance", "System Modeling", and "Root Cause Analysis".

We present the temporal coding of the problem-solving process of the two individuals, JOEY and HAZEL in Figure 2. In the figure, the horizontal spacing of coded events does not necessarily reflect the exact temporal spacing between cognitive events. The results indicate a difference between the problem solving approaches of JOEY and HAZEL, such that how their approaches unfold differently in time. While JOEY seeks system understanding first, HAZEL seeks to understand the system only if it is useful in the root cause analysis process. Other differences include that JOEY expresses uncertainty in system expertise, HAZEL expresses uncertainty in the ill-structured problem, expressing an incoherence between given cues of the problem. JOEY used high visual reasoning through sketching diagrams and HAZEL used none.

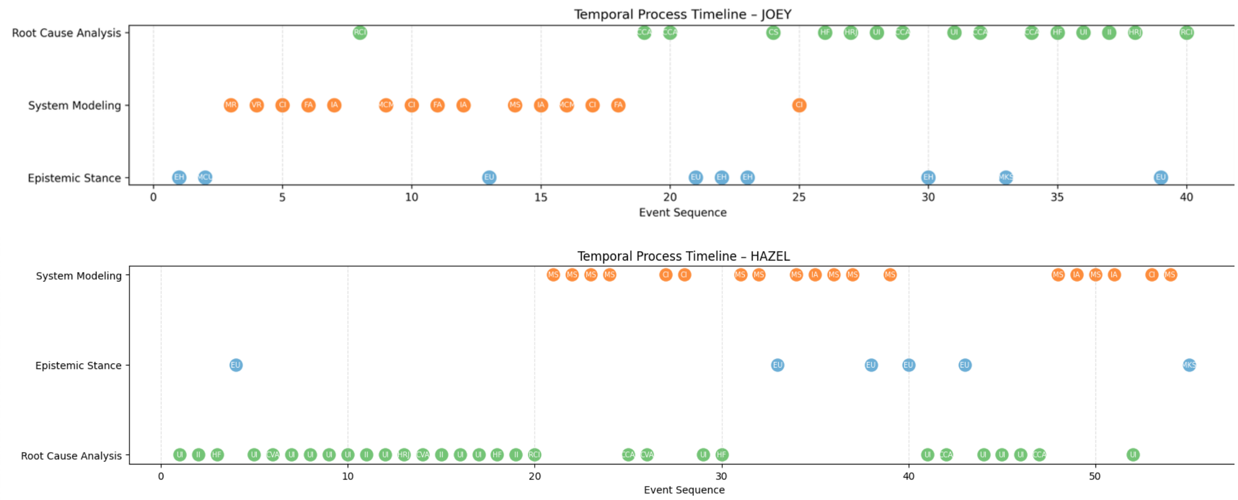

Figure 2. Temporal coding of problem-solving sequence of JOEY and HAZEL, an expert engineer and a PhD student, respectively. The horizontal axes show the sequence of events. The three levels on the vertical axes correspond to the themes of coding.

Semi Structured Interviews. The interview data is coded similarly using a mix of deductive and inductive schemes. Codes included both epistemic stance related and operational ones that defined how individuals performed troubleshooting from a cognitive standpoint. While our data is limited to conduct a quantitative statistical analysis, a few differences were immediately evident from the preliminary analysis of our data. Engineers working in the defense (n=4), biomedical (n=8), and product design (n=13) industries reported a higher number of *situational awareness* during troubleshooting. Engineers in biomedical and product design groups reported experience described by *dealing with ambiguity* at a higher occurence than that of other groups. Engineers with a PhD reported less *collaborative problem solving* that those with BS and MS.

We are interested in producing a model of cognitive tasks of troubleshooting to inform educational interventions for solving complex troubleshooting problems. Our preliminary analysis shows troubleshooting as a non-linear, non-sequential, and a recursive process. To illustrate this non-linear process, we introduce *troubleshooting manifolds*, which are essentially distinct domains of constraint and coordination and are independent of each other when one seeks an understanding and solution of a problem. These manifolds are the following.

System dynamics manifold: The system's behavior, regimes, couplings, and material or computational properties. Its governing logic is causal and dynamical: interventions have effects that may be delayed, nonlinear, distributed, or contingent on operating conditions. Progress at this layer is assessed through changes in behavior, not through persuasiveness of explanation.

Epistemic representation manifold: The enacted structuring of inquiry that determines what is treated as structurally relevant, what counts as legitimate evidence, and how boundaries are drawn around what is worth attending to. Its governing logic is epistemic: it regulates sensemaking by specifying admissible inferences, acceptable uncertainty, and the forms of observation that matter.

Normative manifold: The shifting criteria by which the engineering system's behavior is judged acceptable (i.e. requirements, safety margins, delivery timelines, resource limits, mission priorities, and tolerable risk). Its governing logic is evaluative rather than causal: it determines what counts as "resolved," when the episode can stop, and what tradeoffs are permissible.

Divergence manifold: The experiential registration that adequacy has been violated. Its governing logic is neither causal nor fully evaluative; it is the point at which inadequacy becomes actionable as a demand for inquiry, even if the nature of inadequacy is not yet known.

Situational and stakeholder manifold: The institutional, social, and practical conditions that govern what actions can be taken, by whom, and with what authorization (ex: coordination structures, ownership, escalation pathways, regulatory permissions, safety signoffs, and resource allocations). Its governing logic is juridical and organizational: it distinguishes actions that are epistemically sensible from actions that are permitted, feasible, or appropriate.

We used these definitions to define complexity in troubleshooting. We think that complexity arises when there is misalignment across layers such that movement toward resolution is blocked or destabilized. Depending on which layers are mismatched, one can register a different complexity. For instance, if divergence and situational manifolds are misaligned and one can't understand if the system is indeed faulty, that could be registered as situational complexity.

Conclusions and Future Work

The merits of operationally defining complexity are evident when designing troubleshooting learning environments, which are experiential learning activities, learning scaffolds, quizzes, etc. This demarcation allows us to build specific instructional scaffolds around failure cases. We are currently working identifying and formalizing complexity types, such as information ambiguity, system representation, and stakeholder complexity as mismatch between manifolds of troubleshooting. We plan to conduct additional interviews with engineers who identify as female, as the current sample size is small. Keeping these complexity types in mind, we are authoring case studies both taken from real incidents and as well as preparing constructed ones. We are also preparing instructional scaffolds to help learners navigate these complexities. A few examples include functional block diagrams and flow charts to represent systems/procedures to manage representation complexity, argument maps and purposeful sampling to aid in information ambiguity tagged cases. Cognitive task analysis of expert troubleshooting has identified troubleshooting strategies for navigating ill-structuredness, and these will inform designing instructional scaffolds to have learners identify and use strategies. A few manuscripts on these topics are currently in preparation.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No 2422510. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References:

[1] D. H. Jonassen and W. Hung, "Learning to troubleshoot: A new theory-based design architecture," *Educational Psychology Review,* vol. 18, no. 1, pp. 77-114, 2006.

[2] D. H. Jonassen, *Learning to solve problems: A handbook for designing problem-solving learning environments*. Routledge, 2010.

[3] D. R. Woods, *Successful trouble shooting for process engineers: a complete course in case studies*. John Wiley & Sons, 2006.

[4] A. Schaafstal, J. M. Schraagen, and M. Van Berl, "Cognitive task analysis and innovation of training: The case of structured troubleshooting," *Human factors,* vol. 42, no. 1, pp. 75-86, 2000.

[5] T. Axton, D. Doverspike, S. Park, and G. Barrett, "A model of the information-processing and cognitive ability requirements for mechanical troubleshooting," *International Journal of Cognitive Ergonomics,* vol. 1, no. 3, pp. 245-266, 1997.

[6] S. D. Johnson, "Understanding Troubleshooting Styles To Improve Training Methods," in *The American Vocational Asociation Convention*, Denver, CO, 1995.

[7] A. Schaafstal, "Knowledge and strategies in diagnostic skill," *Ergonomics,* vol. 36, no. 11, pp. 1305-1316, 1993.

[8] K. Perusich, "Qualitatively troubleshooting electronic circuits using fuzzy cognitive maps," in *2007 IEEE International Conference on Electro/Information Technology*, 2007: IEEE, pp. 327-332.

[9] P. Pottier *et al.*, "Exploring how students think: a new method combining think-aloud and concept mapping protocols," *Medical education,* vol. 44, no. 9, pp. 926-935, 2010.

[10] D. R. Dounas-Frazer, K. L. Van De Bogart, M. R. Stetzer, and H. Lewandowski, "Investigating the role of model-based reasoning while troubleshooting an electric circuit," *Physical Review Physics Education Research,* vol. 12, no. 1, p. 010137, 2016.

[11] S. D. Johnsonr and S.-P. Chung, "The effect of thinking aloud pair problem solvings (TAPPS) on the troubleshooting ability of aviation technician students," 1999.

[12] J. Trigg and J. Doulis, "Troubleshooting: What can go wrong and how to fix it," in *Practical Guide to Clinical Computing Systems*: Elsevier, 2008, pp. 105-128.

[13] N. N. Kellam, *Embracing complexity in engineering education*. University of South Carolina, 2006.

[14] J. M. Le Doux and A. A. Waller, "The Problem Solving Studio: An Apprenticeship Environment for Aspiring Engineers," *Advances in Engineering Education,* vol. 5, no. 3, p. n3, 2016.

[15] D. Jonassen, J. Strobel, and C. B. Lee, "Everyday problem solving in engineering: Lessons for engineering educators," *Journal of engineering education,* vol. 95, no. 2, pp. 139-151, 2006.

[16] P. J. Feltovich, R. L. Coulson, and R. J. Spiro, "Learners'(mis) understanding of important and difficult concepts: A challenge to smart machines in education," *Smart machines in education,* pp. 349-375, 2001.

[17] P. J. Feltovich, P. J. Spiro, and R. L. Coulson, "The nature of conceptual understanding in biomedicine: The deep structure of complex ideas and the development of misconceptions," *Center for the Study of Reading Technical Report; no. 440,* 1988.

[18] P. J. Feltovich, R. J. Spiro, and R. L. Coulson, "Learning, teaching, and testing for complex conceptual understanding," in *Test theory for a new generation of tests*: Routledge, 2012, pp. 181-217.

[19] J. A. Hattie and G. M. Donoghue, "Learning strategies: A synthesis and conceptual model," *npj Science of Learning,* vol. 1, no. 1, pp. 1-13, 2016.

[20] K.-L. Cho and D. H. Jonassen, "The effects of argumentation scaffolds on argumentation and problem solving," *Educational Technology Research and Development,* vol. 50, no. 3, pp. 5-22, 2002.

[21] G. Schraw, M. E. Dunkle, and L. D. Bendixen, "Cognitive processes in well-defined and ill-defined problem solving," *Applied cognitive psychology,* vol. 9, no. 6, pp. 523-538, 1995.

[22] N. Shin, D. H. Jonassen, and S. McGee, "Predictors of well-structured and ill-structured problem solving in an astronomy simulation," *Journal of research in science teaching,* vol. 40, no. 1, pp. 6-33, 2003.

[23] R. J. Spiro, P. J. Feltovich, M. J. Jacobson, and R. L. Coulson, "Cognitive flexibility, constructivism, and hypertext: Random access instruction for advanced knowledge acquisition in ill-structured domains," in *Constructivism in education*: Routledge, 1992, pp. 85-107.

[24] H. A. Simon, "The structure of ill structured problems," *Artificial intelligence,* vol. 4, no. 3-4, pp. 181-201, 1973.